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OPTICAL DEVICE INCLUDING DYNAMIC CHANNEL EQUALIZATION

FIELD OF THE INVENTION

The present invention is directed in general to optical devices, and, more

5   particularly, to an optical device including dynamic equalization of optical channel bands

for achieving improved performance in a wavelength division multiplexed system.

Optical communication systems are a substantial and fast growing constituent of

communication networks. The expression "optical communication system," as used

herein, relates to any system that uses optical signals to convey information across an

10   optical waveguiding medium, for example, an optical fiber. Such optical systems include

but are not limited to telecommunication systems, cable television systems, and local area

networks (LANs). Currently, the many optical communication systems are configured to

carry an optical channel of a single wavelength over one or more optical waveguides. To

convey information from plural sources, time-division multiplexing is frequently

15   employed (TDM). In time-division multiplexing, a particular time slot is assigned to

each signal source, the complete signal being constructed from the portions of the signals

collected from each time slot. While this is a useful technique for carrying plural

information sources on a single channel, TDM capacity is limited by fiber dispersion and

the need to generate high peak power pulses.

20   While the need for communication services increases, the current capacity of

existing waveguiding media is limited. Although capacity may be expanded e.g., by

laying more fiber optic cables, the cost of such expansion is prohibitive. Consequently,

there exists a need for a cost-effective way to increase the capacity of existing optical

waveguides.

Wavelength division multiplexing (WDM) has been explored as an approach for increasing the capacity of existing fiber optic networks. WDM systems typically include a plurality of transmitters, each respectively transmitting signals on a designated one of a plurality of channels or wavelengths. The channels are combined by a multiplexer at one

5 end terminal and transmitted on a single fiber to a demultiplexer at another end terminal where they are separated and supplied to respective receivers.

Recently, dense WDM (DWDM) systems transmitting 8 channels on a single fiber have been proposed. These systems can include a demultiplexer having a 1 x 8 optical splitter, which receives the 8 channels on an input fiber, and outputs the channels

10 on each of 8 outputs. The power level on each of the outputs, however, is approximately 1/8 the input power level. Optical components are respectively coupled to the outputs of the 1 x 8 splitter for outputting a corresponding one of the 8 channels, which introduce additional loss.

Although 8 channel WDM systems provide improved capacity, the need for

15 additional capacity has increased with growing Internet traffic and demand for multimedia services. Thus, DWDM systems having higher channel counts are currently being developed. In high channel count systems, however, it is difficult to multiplex and demultiplex a large number of optical channels. For example, in a 40 channel DWDM system, a 1 x 40 splitter would be inadequate to demultiplex each of the channels because

20 the power level at each output of such a splitter would be insufficient to maintain an adequate signal to noise ratio. As a result, the transmitted channels cannot be adequately detected. On the other hand, although an optical amplifier could be used to increase the power on the input of the 1 x 40 splitter, such an amplifier can be difficult to

manufacture, and would fail to provide the requisite optical power per channel at higher channel counts. Moreover, if amplifiers were to be provided at each of the outputs of the 1 x 40 splitter, the cost of the demultiplexer would be excessive.

In addition, signal detection in high channel count, high data rate, and long

5 distance systems can be unreliable as a result of varying signal optical power levels resulting from conventional multiplexing and demultiplexing operations. For example, wavelength dependent variations in the gain or transmission characteristics of network elements can result in significant variations in the optical signal power and signal to noise ratio in the transmitted channels. Attempts have been made to introduce gain-flattening

10 filters at multiplexer/demultiplexer outputs to equalize the channel signal powers, but conventional gain flattening filters also display wavelength-dependent variations in output signal power. Thus the difficulties associated with output signal power variations in the transmitted channels persist.

Thus, there is a need for a multiplexer and demultiplexer suitable for

15 incorporation into a high channel count DWDM system which minimizes power loss and enables adequate detection of the transmitted channels. There is also a need for a scaleable DWDM system, which can readily accommodate additional channels with minimal expense. There is also a need for an optical device for providing channel signal power equalization in wavelength division multiplexed optical communication systems.

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SUMMARY OF THE INVENTION

Consistent with the present invention, an optical device is provided comprising a plurality of separate optical paths, each of which receiving a separate group of optical

signals. Each group of optical signals is provided to an associated variable optical attenuator. Separate inputs of an optical combiner are each coupled to an output of an associated one of the variable optical attenuators. The optical combiner has an output providing the separate groups of optical signals in an aggregated form on an aggregate

5 optical signal path.

An optical performance monitor is coupled to the aggregate optical signal path, and is configured to detect an optical signal power of each of the separate groups. The monitor be provided in a variety of configurations, and may include, for example, a spectrum analyzer and an appropriately programmed processor circuit. The monitor supplies a

10 feedback signal to corresponding ones of the variable optical attenuators for adjusting a respective attenuation associated with each of the attenuators in dependence of the detected optical signal powers.

The combiner may be provided in a variety of configurations. In one exemplary embodiment, the combiner may include a plurality of cascaded optical filters, each of the

15 optical filters having an input coupled to an output of an associated one of the variable optical attenuators. Also, an amplifier and/or a gain-flattening filter may be coupled to the aggregate optical signal path.

In a multiplexer configuration, the device may further include a plurality of first optical combiners, each of which being coupled to an associated one of the optical paths

20 for supplying a respective one of the separate groups of optical signals. In a line amplifier configuration, the device may further include an optical separator having a plurality of outputs, each of which being coupled to an associated one of the optical paths for supplying a respective one of the separate groups of optical signals.

In a demultiplexer configuration, a device consistent with the invention may include an optical communication path receiving an optical signal including a plurality of separate wavelengths. The optical performance monitor may be coupled to the optical communication path. An optical separator receives an output of the optical performance

5 monitor, and supplies each of the plurality of groups of the separate wavelengths on a separate associated output. Each of a plurality of variable optical attenuators receives a separate one of the separate associated outputs for adjusting an associated attenuation level.

A method for dynamically equalizing power levels associated with groups of optical

10 signals consistent with the invention includes the steps of: providing each of the groups of optical signals on separate optical signal paths; combining each of the groups of optical signals on an aggregate optical signal path; detecting the power level associated with each of the groups of optical signals on the aggregate optical signal path; and attenuating each group of the optical signals on the separate signal paths in dependence of

15 an associated detected power level. In a demultiplexer application, another exemplary method of dynamically equalizing power levels associated with groups of optical signals, includes the steps of: providing the groups of optical signals in an aggregated form on an optical signal path; detecting the power level associated with each of the groups of optical signals on the optical signal path; separating the groups of optical signals onto associated

20 separate optical signal paths; attenuating each group of the optical signals on the associated separate signal paths in dependence of an associated detected power level.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention will be apparent from the following detailed description of the presently preferred embodiments thereof, which description should be considered in conjunction with the accompanying drawings in which:

Fig. 1 illustrates a schematic diagram of an optical demultiplexer in accordance

5   with the present invention;

Fig. 2 illustrates a schematic diagram of an interference filter;

Fig. 3 illustrates transmittance characteristics of filtering elements 125-1, 125-2 and 125-3 shown in Fig. 1;

Fig. 4 illustrates transmittance characteristics of filtering elements 130-1 and 130-

10   2 shown in Fig. 1;

Fig. 5 illustrates plots of loss vs. channel count for the present invention and a conventional demultiplexer;

Fig. 6 illustrates an additional embodiment of the present invention;

Fig. 7 illustrates an example of a sub-demultiplexer;

Fig. 8 illustrates an additional example of a sub-demultiplexer;

15   Fig. 9 illustrates a further example of a sub-demultiplexer;

Fig. 10 illustrates a fiber optic coupler demultiplexer for separating two wavelengths;

Fig. 11 illustrates an additional embodiment of the present invention;

Fig. 12 illustrates an optical multiplexer in accordance with an aspect of the

20   present invention;

Fig. 13 illustrates an optical multiplexer in accordance with a further aspect of the present invention;

Fig. 14 illustrates a filtering element shown in Fig. 13;

Fig. 15 illustrates a cross-sectional view of an exemplary optical attenuator shown in Fig. 13;

Fig. 16 illustrates a side view of an optical attenuator shown in Fig. 15;

Fig. 17 illustrates a side view of the optical attenuator after fusion splicing.

5   Fig. 18 illustrates a schematic diagram of an optical multiplexer including a dynamic equalization system consistent with the present invention;

Fig. 19 illustrates a schematic diagram of an optical demultiplexer including a dynamic equalization system consistent with the present invention; and

Fig. 20 illustrates a schematic diagram of an optical amplifier including a dynamic equalization system consistent with the present invention.

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DETAILED DESCRIPTION

In accordance with the present invention, optical channels to be demultiplexed are supplied to first and second optical fibers via an optical splitter. Low loss interference

15   filters, for example, coupled to the first and second optical fibers, select respective groups of channels. Each group of channels is next demultiplexed with sub-demultiplexers into individual channels, each of which is then sensed with a corresponding photodetector. Although the optical splitter introduces an optical power loss at the input to the

20   demultiplexer, the interference filters and sub-demultiplexers create little additional loss. As a result, the total power loss associated with the present invention is significantly less than that obtained with a conventional n channel demultiplexer based on a 1 x n splitter.

Accordingly, large numbers of channels, e.g., in excess of forty can be readily demultiplexed and detected.

Turning to the drawings in which like reference characters indicate the same or similar elements in each of the several views, Fig. 1 illustrates optical demultiplexer 100

5 consistent with the present invention. As discussed in greater detail below, the exemplary demultiplexer illustrated in Fig. 1 demultiplexes 40 channels. The present invention, however, is not limited to this number of channels. Rather, the present invention is applicable to demultiplexers that can separate any appropriate number of optical channels.

Returning to Fig. 1, optical demultiplexer 100 receives, for example, a plurality of

10 multiplexed optical channels λ_1 - λ_{40} on input optical fiber 105. The multiplexed channels are emitted by laser transmitters (not shown) coupled to optical fiber 105. The multiplexed channels are supplied to the input of optical splitter 110, which supplies channels λ_1 - λ_{40} to first and second output fibers 115 and 120, respectively. Optionally, optical amplifier 101 may be provided at the input of coupler 110 in order to offset any

15 loss introduced by splitter 110. Alternatively, the loss imposed by splitter 110 can be compensated by coupling optical amplifiers to output fibers 115 and 120.

As further shown in Fig. 1, first optical filtering elements 125-1 to 125-3 are coupled to first output fiber 120, and second filtering elements 130-1 and 130-2 are

20 coupled to second output fiber 115. Each of these filtering elements typically includes an interference filter commercially available from JDS Fitel or DiCon, for example.

A simplified diagram of filtering element 125-1 incorporating an interference filter, for example, is illustrated in Fig. 2. Filtering element 125-1 receives channels λ_1-

8

λ_{40} on input fiber 210 having an end portion spaced from graded refractive index (GRIN)

lens 215. As a result, light emitted from the end portion diverges prior to impinging on

lens 215. Channels λ_1-λ_{40} are collimated by lens 215 and directed toward dielectric thin

film filter 220. Thin film filter 220 includes a substrate coated with a plurality of thin

5   dielectric films of appropriate thickness and number to pass, in this case, channels λ_1-λ_8,

and reflect channels λ_{17}-λ_{40}. Channels λ_1-λ_8 are thus transmitted to GRIN lens 218 where

they are focused onto an end portion of output fiber 235 and transmitted to a

corresponding sub-demultiplexer via output port 240 of filtering element 125-1.

Channels λ_9-λ_{40}, however, are reflected back to GRIN lens 215, focused onto fiber 225

10   and output through port 230 to filtering element 125-2, which along with filtering

element 125-3, typically has a similar construction as filtering element 125-1.

The transmittance vs. wavelength characteristics of filtering elements 125-1 to

125-3 are shown in Fig. 3. Transmittance band 325-1 of filtering element 125-1 has a

relatively high transmittance over a range of wavelengths including the first eight

15   channels, λ_1-λ_8. As noted above, therefore, these channels are transmitted toward an

output port of filtering element 125-1. It should be noted, however, that channels λ_9-λ_{11},

for example, are also transmitted, but only partially, since they lie in the roll-off region

324 of transmittance band 325-1. Remaining channels λ_{12}-λ_{40}, as well as channels λ_9-λ_{11}

at a substantially reduced power level, are reflected to filtering element 125-2 having

20   high transmittance band 325-2. As a result, channels λ_{17}-λ_{24} are transmitted toward the

output port of filtering element 125-2. As further shown in Fig. 3, however, channels

λ_{25}-λ_{27}, for example, adjacent λ_{17}-λ_{24} are also transmitted, but to a lesser extent.

Remaining channels λ_{28}-λ_{40} are reflected and output to filtering element 125-3 of which

channels λ_{33}-λ_{40} fall within high transmittance band 325-3 and are thus passed to an output port of filtering element 125-3. Channels λ_{28}-λ_{31}, however, are partially transmitted.

As further shown in Fig. 1, channel groups λ_1-λ_8, λ_{17}-λ_{24}, and λ_{33}-λ_{40} are

5   respectively directed to sub-demultiplexers 135-1, 135-2 and 135-3 where further demultiplexing is performed to output individual channels on corresponding output ports. These output ports, in turn, are coupled to respective ones of photodiodes 150 where the channels are converted into electrical signals for processing by appropriate circuitry (not shown). The term sub-demultiplexer is used herein to describe an optical apparatus that

10   demultiplexes the groups of channels respectively output from the filtering elements. Sub-demultiplexers 135-1, 135-2 and 135-3 are discussed in greater detail below.

As noted above, channels lying outside the high transmittance bands of filtering elements 125-1, 125-2 and 125-3 are only partially reflected due to the relatively broad roll-off regions of the transmittance characteristics of interference filters, for example.

15   Accordingly, channels adjacent the intended channel sub-groups incur a significant amount of power loss and cannot be effectively demultiplexed. These channels are therefore supplied by filtering elements 130-1 and 130-2 coupled to second output fiber 115, as discussed in greater detail below with reference to Fig. 4.

As shown in Fig. 4, filtering element 130-1 has high transmittance band 430-1

20   extending over wavelengths λ_9-λ_{16}. Filtering element 130-1 typically has a similar construction to filtering element 125-1, and therefore transmits channels λ_9-λ_{16} for output to corresponding sub-demultiplexer 140-1 and further demultiplexing. Remaining channels λ_1-λ_8 and λ_{17}-λ_{40} are reflected to filtering element 130-2 having high

transmittance band 430-2 encompassing channels λ_{25}-λ_{32}. Accordingly, channels λ_{25}-λ_{32} are transmitted through filtering element 130-2 and directed toward sub-demultiplexer 140-2 for further demultiplexing into individual channels.

Channels lying adjacent the high transmitttance bands 430-1 and 430-2, like those

5   channels discussed previously adjacent high reflectance bands 325-1 to 325-3, are partially transmitted by filtering elements 130-1 and 130-2 and are thus difficult to detect after further demultiplexing. These channels, however, lie within the high transmittance bands of filtering elements 125-1 to 125-3 and are thus demultiplexed through sub-demultiplexers 135-1 to 135-3, respectively, as noted above. Therefore, in the presently

10   described example of the present invention, first output fiber 120, filtering elements 125-1 to 125-3 and corresponding sub-demultiplexers 135-1 to 135-3, serve to demultiplex channels λ_1-λ_8, λ_{17}-λ_{24} and λ_{33}-λ_{40}, respectively. Additionally, second output fiber 120, filtering elements 130-1 and 130-2 and corresponding sub-demultiplexers 140-1 and 140-2 serve to demultiplex channels λ_9-λ_{16} and λ_{25}-λ_{32}, respectively. Accordingly, alternating

15   groups of channels are respectively selected by filtering elements 125-1 to 125-3 and 135-1 to 135-3.

Alternatively, if only 40 channels are to be separated by the demultiplexer in accordance with the present invention, filtering elements 130-2 and 125-3 can be omitted and sub-demultipelxers 140-2 and 135-3 can be coupled directly to the outputs of

20   filtering elements 130-1 and 125-2, respectively.

Filtering elements 125-i to 125-3, 130-1 and 130-2 introduce little power loss to the selected sub-groups of channels. For example, the power loss associated with the channels reflected by the filtering elements is typically about 0.5 dB, and the loss

associated with the channels transmitted through the filtering elements is about 0.7 dB. Thus, the overall loss of the demultiplexer in accordance with the present invention is significantly reduced.

It is noted that as the channels propagate down one of output fibers 115 or 120 in

5   Fig. 1, the transmission loss through each filtering element can accumulate. However, since the loss associated with each filtering element is so low, channels can pass through four filtering elements along one of output fibers 115 and 120, and incur less than 3 dB of loss. Accordingly, additional channels can be demultiplexed with little additional loss simply by concatenating additional filtering elements with fiber patch cord, for example,

10   between adjacent couplers. Alternatively, filtering elements can be easily added by coupling the output of one filtering element to one end of an optical fiber via a first fiber optic coupler and coupling the other end of the optical fiber to another filtering element via a second fiber optic coupler. Thus, the demultiplexer in accordance with the present invention is readily expandable and upgradeable to accommodate more channels with

15   minimal expense and relatively little loss.

Fig. 5 illustrates loss L as a function of channel count n in accordance with the present invention (curve 910) and a conventional 1 x n splitter based demultiplexer (curve 920). As seen in Fig. 5, at low channel counts, the loss associated with the present invention is higher than the conventional demultiplexer. This is due to the loss

20   introduced by the 1 x 2 splitter 110, which imposes a minimum loss in the demultiplexer. At higher channel counts, however, the loss associated with the conventional demultiplexer increases linearly with n (curve 920). On the other hand, the loss associated with the present invention (curve 910) is stepped and increases at a much more

gradual rate due, at least in part, to the low loss of the filtering elements. Therefore, at higher channel counts, channels demultiplexed in accordance with the present invention experience less loss than those demultiplexed with a conventional 1 x n splitter.

Fig. 6 illustrates an alternative embodiment in which each filtering element constitutes a combination of a circulator and grating. In particular, filtering element 130-1 includes a circulator 830-1 receiving channels λ_{1-40} at a first circulator port 831-1 coupled to output fiber 115. These channels are circulated to port 831-2 and output to in-fiber Bragg grating 832-1, which is configured to have a high reflectivity band that coincides with the band of channels λ_{9-16}. Accordingly, channels λ_{9-16} are reflected back to port 831-2 while the remaining channels are transmitted to circulator 830-2. Channels λ_{9-16} are then circulated to output port 831-3 and supplied to a corresponding sub-demultiplexer. In a similar fashion circulators 830-2, 825-1, 825-2 and 825-3 output channel groups λ_{25-32}, λ_{1-8}, λ_{17-24} and λ_{33-40} in conjunction with in-fiber Bragg gratings 832-2, 832-3, 832-4, and 832-5, respectively.

Typically, in-fiber Bragg gratings 832-3, 832-4 and 832-5 reflect successively lower bands or wavelengths, such that the wavelengths in channel group λ_{1-8} are greater than the wavelengths in channel group λ_{17-24}, and the wavelengths in channel group λ_{17-24} are greater than the wavelengths in channel group λ_{33-40}. Further, in-fiber Bragg gratings 831-1 and 832-2 reflect successively lower bands of wavelengths. As a result, the demultiplexer shown in Fig. 6 avoids cladding or radiation mode loss.

Examples of sub-demultiplexers will next be described with reference to Figs. 7-10. Although exemplary configurations are discussed in detail with respect to sub-demultiplexer 133-1, it is understood that the remaining sub-demultiplexers described

above can have a similar structure. Moreover, the present invention is not limited to these specific sub-demultiplexer configurations nor the specific number of inputs and outputs disclosed. Rather, it is understood that any optically demultiplexing component capable of demultiplexing a group of channels can be used.

5   Fig. 7 illustrates a first exemplary construction of sub-demultiplexer 133-1. As shown in Fig. 7, sub-demultiplexer 133-1 receives channels λ_1-λ_8 at an input 525 of a 1 x 8 splitter 515, commercially available from IOT, for example. Splitter 515 has eight outputs, each of which supplying channels λ_1-λ_8 to a corresponding one of eight optical selectors 530. Splitter 515, as well as splitter 110, may include a waveguide doped with an optically active material, such as erbium. Such a waveguide may further be optically

10   pumped so that splitter 515 has reduced loss or provides optical gain.

In Fig. 7, only one of the selectors is shown including a three port circulator 510 having a first port 510-1 for receiving channels λ_1-λ_8 from one of the outputs of splitter 515. These channels are transmitted to in-fiber Bragg grating 520 via second port 510-2

15   of circulator 510. Typically, in-fiber Bragg grating 520 has a reflectance characteristic as a function of wavelength such that a reflectivity maximum is obtained at a desired channel or wavelength, e.g., λ_1. Thus, only channel λ_1 is reflected back to second port 510-2 and circulated to third circulator port 510-3, which outputs channel λ_1 to one of photodiodes 150 for subsequent detection and further processing. Likewise, the in-fiber

20   Bragg gratings in the remaining selectors have reflectivity maxima that respectively reflect a corresponding one of each of remaining wavelengths λ_2-λ_8 for output to one of photodiodes 150.

Fig. 8 illustrates an alternative construction for sub-demultiplexer 133-1. Here, the channel group λ_1-λ_8 is supplied to a planar arrayed waveguide grating (AWG) 610 or dielectric thin film demultiplexer, which supplies a respective channel on each of outputs 610-1 to 610-8. If the spacing between adjacent ones of channels λ_1-λ_8 is relatively

5   narrow, AWG 610 can introduce an unacceptably high level of undesired cross-talk. Accordingly, additional filtering may be required. Thus, a selector 630 is further illustrated in Fig. 8 to isolate a single channel, e.g., λ_1, and remove any cross-talk. In this case, selector 630 includes a coupler 655 receiving substantially channel λ_1 at a first port 655-1. The input light is next supplied to in-fiber Bragg grating 640 through second port

10   655-2. In-fiber Bragg grating 640 substantially reflects only channel λ_1, while passing other wavelengths. Thus, channel λ_1 is reflected back to second port 655-2 and output to one of photodiodes 150 via third output port 655-3 of coupler 655.

As further shown in Fig. 8, feedback circuit 670 is optionally provided to insure that grating 640 reflects at the intended wavelengths. As is generally understood, an in-

15   fiber Bragg grating typically includes a periodic variation of index of refraction, with the spacing between refractive index peaks defining, in part, the wavelength to be reflected by the grating. Variations in the wavelength of light reflected by grating 640 can be sensed with photodiode 660, which supplies an electrical signal to a feedback circuit 670. Feedback circuit 670, in turn, generates an appropriate voltage signal to adjust a

20   temperature regulator coupled to grating 640. Since the grating refractive index spacing changes with temperature, the temperature of the grating is set by feedback circuit 670 to alter the grating spacing so that grating 640 reflects a desired wavelength.

Fig. 9 illustrates a further exemplary construction of sub-demultiplexer 133-1. In this instance, sub-demultiplexer 133-1 comprises a plurality of Mach-Zehnder interferometers. It is known that Mach-Zehnder interferometers, which include optical waveguides of varying lengths, can be used to separate wavelengths (see for example,

5   published European Patent Application EP0482461). Accordingly, as shown in Fig. 9, Mach-Zehnder interferometers can be cascaded to separate a group of wavelengths. For example, Mach-Zehnder interferometer 710 separates input channels λ_1-λ_8 into sub-groups of channels $\lambda_{1,3,5,7}$ and $\lambda_{2,4,6,8}$, respectively. Channel sub-group $\lambda_{1,3,5,7}$ is supplied to Mach-Zehnder interferometer 715 and channel sub-group $\lambda_{2,4,6,8}$ is supplied

10 to Mach-Zehnder interferometer 720. As further shown in Fig. 9, Mach-Zehnder interferometers 715 and 720 further break down these channel sub-groups to channel pairs $\lambda_{1,5}$, $\lambda_{3,7}$, $\lambda_{2,6}$, and $\lambda_{4,8}$, which are further demultiplexed into individual channels by Mach-Zehnder interferometers 725, 730, 735 and 740, respectively.

Fiber optical couplers, commercially available from Applied Fiber Optics, Inc.

15 and Gould, for example, can also be used to demultiplex the groups of channels supplied by the filtering elements. Fiber optic coupler 1000 is illustrated in Fig. 10 in which two wavelengths λ_i and λ_j, are separated and supplied on respective outputs 1010 and 1020. A plurality of such fiber optic couplers can be cascaded in a manner similar to that shown in Fig. 9 to thereby demultiplex a plurality of wavelengths within a given group of

20 channels. If necessary, selectors 530 or 630 may be provided at the outputs of Mach-Zehnder interferometers 725, 730, 735 and 740 of Fig. 7, or at the outputs of the cascaded fiber optic couplers 1000, in order to reject any extraneous wavelengths, e.g., cross-talk.

Fig. 11 shows an alternative embodiment of the present invention, whereby splitter 110 and filtering elements 125-1 to 125-3, 135-1 and 135-2 are replaced by five port circulator 1110 and in-fiber Bragg gratings 1111 to 1114. Channels λ_{1-40} are supplied to a first port 1110-1 of circulator 1110 and are output through port 1110-2. In-

5   fiber Bragg grating 1114 is configured to transmit channels λ_{1-8} and reflect channels λ_{9-40}. Accordingly, channels λ_{1-8} are supplied to sub-demultiplexer 1120-1 for further demultiplexing while channels λ_{9-40} are reflected back to second port 1110-2 and output to port 1110-3. In-fiber Bragg grating 1113, which is coupled to second port 1110-3, is configured to reflect channels λ_{17-40} and transmit channels λ_{9-16}. As a result, channels λ_{9-}

10    $_{16}$ are passed to sub-demultiplexer 1120-2 for further demultiplexing and channels λ_{17-40} are reflected back to port 1110-3 and output through port 1110-4.

In-fiber Bragg gratings 1112 and 1111, coupled to corresponding ports 1110-4 and 1110-5, are configured to transmit channel groups λ_{17-24} and λ_{25-32}, respectively, and reflect the remaining channels. Thus, channel groups λ_{17-24} and λ_{25-32} are selected in a

15   manner similar to that described above, and supplied to corresponding sub-demultiplexers 1120-3 and 1120-4 for further demultiplexing. In addition, channels λ_{33-40} are output through port 1110-6 and supplied to sub-demultiplexer 1120-5 for further demultiplexing. Typically, sub-demultiplexers 1120-1 to 1120-5 have a structure similar to that shown in Fig. 7.

20   Fig. 12 illustrates optical multiplexer 1200 in accordance with the present invention for multiplexing forty channels onto a single fiber 1205. As seen in Fig. 12, each channel input to multiplexer 1200 is supplied on a respective input optical communication path or line to one of optical combiners 1211 to 1215. Optical combiners

1211 to 1215 can be similar to optical splitter 515, but with the inputs and outputs reversed. As further shown in Fig. 12, combiner 1211 receives channels λ_1-λ_8 on respective input lines and combines these channels as a channel group onto a single output line 1231. Likewise, channel groups λ_9-λ_{16}, λ_{17}-λ_{24}, λ_{25}-λ_{32}, and λ_{33}-λ_{40} are output

5   from combiners 1212, 1213, 1214 and 1215 on lines 1232, 1233, 1234 and 1235, respectively. Lines 1231 and 1232 are fed to an additional combiner such as a filtering element 1221, commercially available from JDS Fitel or E-Tek, for example, for combining channel groups λ_1-λ_8 and λ_9-λ_{16} onto line 1241. Lines 1234 and 1235 are coupled to filtering element 1223, which combines λ_{25}-λ_{32} and λ_{33}-λ_{40} onto a single line

10   1236, and lines 1233 and 1236 are fed to filtering element 1222, which combines channel groups λ_{17}-λ_{24}, λ_{25}-λ_{32}, λ_{33}-λ_{40} onto a single line 1242. Lines 1241 and 1242 are connected to coupler 1231, similar in construction to splitter 110 but having the inputs and outputs reversed, for combining channel groups λ_1-λ_8, λ_9-λ_{16}, λ_{17}-λ_{24}, λ_{25}-λ_{32}, and λ_{33}-λ_{40} onto line 1205.

15   Optical multiplexer 1200 is readily expandable by adding additional combiners and filtering elements.

Fig. 13 illustrates an alternative optical multiplexer 1300, in accordance with a further aspect of the present invention, which can also multiplex a relatively large number of channels. Optical multiplexer 1300 is shown multiplexing 80 channels, but any

20   appropriate number of channels can be suitably multiplexed with the multiplexer in accordance with the present invention.

Multiplexer 1300 includes a plurality of conventional 1 x 8 combiners 1310-1 to 1310-10, for example, each having eight inputs receiving a respective one of eight

channels. Combiners 1310-1 to 1310-10 can include one or more of the following: dielectric filters, fiber couplers, planar waveguides, arrayed waveguide routers, and appropriate combinations of fiber Bragg gratings and circulators. Combiners 1310-1 to 1310-10 combine the received channels onto corresponding outputs, which are coupled to respective optical attenuators 1312-1 to 1312-9. A series of cascaded combiners, including for example optical filter elements 1314-1 to 1314-9, generally receive optical signal inputs from corresponding optical attenuators 1312-1 to 1314-9, and add these signals to signals input from a preceding optical filter element. In particular, filter element 1314-1 adds channels λ_1 to λ_8 received from combiner 1310-1 and channels λ_9 to λ_{16} output from combiner 1310-2 via attenuator 1312-1. The aggregated channels, channels λ_1 to λ_{16}, are passed to filtering element 1314-2, which adds channels λ_{17} to λ_{24} output from attenuator 1312-2 thereto. In a similar fashion channel groups λ_{25} to λ_{32}, λ_{33} to λ_{40}, λ_{41} to λ_{48}, λ_{56} to λ_{64}, and λ_{72} to λ_{80} are successively added by filters 1314-3 to 1314-9. The final filtering element stage 1314-9 outputs the entire aggregation of channels, λ_1 to λ_{80} onto a single output fiber 1316.

An exemplary filtering element 1314-1 is illustrated in greater detail in Fig. 14. Filtering element 1314-1 has a similar construction as that shown in Fig. 2. For example, channels λ_9 to λ_{16} are added to channels λ_1 to λ_8 by supplying channels λ_9 to λ_{16} through port 1406 and channels λ_1 to λ_8 through port 1410. Channels λ_9 to λ_{16} are emitted from an end of fiber 1422, collimated by lens 1424 and transmitted through dielectric filter 1414. Dielectric filter 1414 typically includes a transparent substrate coated with a plurality of dielectric layers configured to transmit, in this case, a band of wavelengths including channels λ_9 to λ_{16} to lens 1412. Channels λ_9 to λ_{16} are then focused onto an

end of output fiber 1420. Channels λ_1 to λ_8, however, are emitted from an end of fiber 1408, collimated by lens 1412, and reflected dielectric filter 1414, which reflects wavelengths outside the λ_9 to λ_{16} band. Channels λ_1 to λ_8 are next focused onto the end of output fiber 1420, and are thus added with channels λ_9 to λ_{16}.

5   Channels λ_1 to λ_8, however, incur a loss when combined with channels λ_9 to λ_{16} in filtering element 1314-1, and experience further loss when combined with remaining channels λ_{17} to λ_{72} in filtering elements 1314-2 to 1314-9. Likewise, channels λ_9 to λ_{72} accumulate varying degrees of loss when output from combining filters 1314-2 to 1314-9. Thus, in the absence of attenuators 1312-1 to 1312-9, channels output from

10   multiplexer 1300 have unequal optical power. In WDM systems, however, substantially uniform channel power is desirable, because optical amplifiers downstream from the multiplexer may otherwise substantially degrade the optical signal-to-noise ratio of the low power channels. In addition, noise in a receiver can adversely affect detection of low power signals.

15   In order to insure, therefore, that each channel output from multiplexer 1300 has substantially the same optical power, attenuators 1312-1 to 1312-9 are provided to impose an additional loss on channels input to filtering elements 1314-1 to 1314-9. The amount of attenuation for each attenuator is typically selected based on the number of filtering elements separating the attenuator from output fiber 1316. For example, the

20   attenuation of attenuator 1312-1 is less than that of attenuators 1312-2 to 1312-9 because optical signals passing through attenuator 1312-1 will incur further loss passing through filtering elements 1314-2 to 1314-9. In contrast, since optical signals output from combiner 1310-10 do not pass through a series of dielectric filters and thus experience

relatively little loss, the attenuation associated with attenuator 1312-9 is greater than that of the remaining attenuators so that substantially uniform optical power can be achieved for each channel output on fiber 1316. Optionally, an attenuator may be provided at the output of combiner 1310-1, if necessary.

5   Optical attenuator 1312-1 will next be described with reference to Figs. 15 and 16. It is understood that optical attenuators 1312-2 to 1312-9 typically have a similar construction. Moreover, the structure of optical attenuator 1312-1 is exemplary, and other optical attenuator configurations are considered within the scope of the invention.

As seen in Fig. 16, optical attenuator 1312-1 includes two optical fibers 1610 and 1620 joined at respective end portions. As further shown in Fig. 15, which is a cross-sectional view of optical attenuator 1312-1 taken along line 1630, fibers 1610 and 1620 further include core regions 1520 and 1510, and cladding regions 1530 and 1540, as commonly understood. Generally, the refractive indices of the core and cladding are selected so that light propagating through fibers 1610 and 1620 is confined to the cores thereof. In addition, the cores and claddings of both fibers are typically provided about respective axes, as is generally known.

As further shown in Figs. 15 and 16, the axes and thus the cores of fibers 1610 and 1620 are offset from one another by a distance d. Thus a portion of light passing from fiber 1620 to fiber 1610, for example, is dispersed at interface 1635 of the two fibers, while the remaining portion of the light passes through fiber 1610. As a result, light transmitted through interface 1635 experiences loss, and is thus attenuated. The amount of attenuation is determined by offset d; a relatively small offset distance d yields less attenuation while a greater offset distance provides more attenuation.

Typically, offset distance d is adjusted for each of attenuators 1312-1 to 1312-9 so that a different attenuation can be obtained for each attenuator, and as discussed above, substantially equalized optical power can be achieved for each channel output from multiplexer 1300.

Typically, fibers 1610 and 1620 are fusion spliced, so that outer surfaces of these fibers are smooth and continuous at interface 1630, as shown in Fig. 17. The cores of the fibers, however, remain offset to provide a desired attenuation, as discussed above.

Multiplexer 1300 has a relatively simple construction and does not require couplers, as is the case with multiplexer 1200 discussed above with reference to Fig. 12.

Turning now to FIG. 18, there is shown a multiplexer 1800, in accordance with a further aspect of the invention, which includes an exemplary dynamic equalization system including a plurality of variable optical attenuators controlled by feedback signals from an output monitor. Optical multiplexer 1800 is shown multiplexing 80 channels, but dynamic equalization consistent with the present invention can be provided in a device for appropriately processing any number of channels.

In the illustrated exemplary embodiment, multiplexer 1800 includes a plurality of conventional 1x8 combiners 1810-1 to 1810-10, each having eight inputs receiving a respective one of eight channels of an 80-channel system. Combiners 1810-1 to 1810-10 can include one or more of the following: dielectric filters, fiber couplers, planar waveguides, arrayed waveguide routers, and appropriate combinations of fiber Bragg gratings and circulators. Combiners 1810-1 to 1810-10 combine the received channels onto corresponding outputs, which are coupled to respective conventional variable optical attenuators 1812-1 to 1812-10.

The outputs of the variable optical attenuators 1812-1 to 1812-80 are provided to a combiner 1814. The combiner may include a series of optical filter elements, as shown, for example in FIG. 13, which generally receive optical signal inputs from corresponding optical attenuators 1812-1 to 1812-10 and add these signals to signals input from a

5 preceding optical filter element. It is to be understood, however, that a dynamic equalization system consistent with the invention may be incorporated into a multiplexer having a combiner 1814 constructed in any manner consistent with the present invention, or, alternatively, in a manner known in the art.

The output of the combiner comprises the aggregation of channels, λ_1 to λ_{80}, and

10 is typically provided on a single output fiber 1816 as an input to a conventional optical amplifier 1818, e.g. a rare earth doped fiber amplifier. The amplifier is provided for amplifying the aggregated channels λ_1 to λ_{80} approximately to a level that is appropriate for achieving reliable detection of the aggregated channels at a receiver or further amplifier site downstream therefrom. As noted above with respect to Fig. 13, different

15 groupings of channels can experience varying degrees of loss when combined onto a single fiber, particularly when a multiplexer, such as that shown in Fig. 13 is used. Accordingly, as further noted above, in systems without an equalization system, it has been found that each of the aggregated bands λ_1 to λ_8, λ_9 to λ_{16}, ...λ_{73} to λ_{80}, for example, may be at a different optical signal powers at the output of the combiner. Since

20 the gain spectrum of a downstream amplifier can be non-uniform, variations in the band optical signal powers can result in degraded system performance, often seen as increased bit-error-rates.

To mitigate the adverse effects of optical signal power variation in the aggregated channels, the output of the amplifier on line 1820 may be provided as an input to a conventional gain flattening filter 1822, which typically includes a dielectric filter configured to selectively attenuate various channels to thereby offset unequal channel

5   powers output from amplifier 1818. As a result, the output of the gain flattening filter on line 1824 comprises the aggregated signal bands with approximately equalized optical signal powers. It has been recognized, however, that the output signal power of the gain-flattening filter too may vary as a function of wavelength, but is approximately constant within a single band of channels.

10   Consistent with the invention, therefore, an optical tap 1833, including a conventional optical splitter, supplies 1-5% of the optical power from filter 1822 to an optical performance monitor circuit 1826 for detecting the optical signal power, and optionally the optical signal to noise ratios, at each band of channels. Based on the detected signal powers and/or signal to noise ratios, the monitor 1826 is configured to

15   generate suitable feedback signals to control the attenuation levels of the variable optical attenuators 1812-1 to 1812-10 for dynamically equalizing the optical signal powers of the bands in the aggregated signal. The present embodiment differs from the embodiment described above in that variable optical attenuators 1812-1 to 1812-10 are provided instead of fixed attenuators 1312-1 to 1312-9 discussed above.

20   A variety of monitor configurations for providing a feedback signal are possible. For example, the monitor may include a conventional optical spectrum analyzer 1830 and a processor circuit 1832 appropriately programmed or otherwise configured for generating the feedback signals, as illustrated in FIG. 18. In addition, the feedback

signals may be provided through a hard-wire connection, e.g. on lines 1828-1 to 1828-10, as shown, or may be provided to the attenuators through a telemetry channel.

Advantageously, feedback from the monitor 1826 to the variable optical attenuators 1812-1 to 1812-10 facilitates dynamic equalization of the optical signal power

5   levels of each band in the aggregate output on line 1834. The adverse effects of wavelength-dependent variations in the output of the amplifier and the gain-flattening filter are thereby substantially eliminated, resulting in improved system performance.

Although the advantages of dynamic equalization consistent with the invention may be applied to a wide variety of optical systems, it is particularly advantageous in high

10   channel count, high bit rate, and long distance systems. Also, it is to be understood that in some applications, e.g. in applications with relatively low channel-count, the amplifier and/or the gain-flattening filter may not be necessary.

FIG. 19 illustrates an exemplary demultiplexer 1900 including a dynamic equalization system consistent with the invention. As shown, input to the demultiplexer

15   comprises an aggregation of channels, e.g. λ_1 to λ_{80}, and may be provided on a single input fiber 1940 as an input to a conventional optical amplifier 1918, e.g. a rare earth doped fiber amplifier. The amplifier is provided for amplifying the aggregated channels approximately to a level that is appropriate for achieving reliable detection of the aggregated channels at a receiver or amplifier site (not shown).

20   The output of the amplifier on optical path 1942 may be provided as an input to a conventional gain flattening filter 1922. The output of the gain-flattening filter comprises the aggregated signal with approximately equalized optical channel powers. Again, the

output signal power of the amplifier and the gain flattening filter varies as a function of wavelength, but is approximately constant within single bands of channels.

To equalize the optical signal powers of the bands, an optical tap 1933, similar to tap 1833, is coupled to filter 1922 to supply the optical performance monitor 1926 with a

5 portion of the output from fitler 1922 for detecting the optical signal power, and optionally the optical signal to noise ratios, at each band of channels. The output of the monitor 1926 is coupled to an optical demultiplexer or separator 1944. The separator separates aggregated channels into channel bands λ_1 to λ_8, λ_9 to λ_{16}, ... λ_{73} to λ_{80} on separate outputs, which are coupled to respective corresponding variable optical

10 attenuators 1912-1 to 1912-10. The attenuators provide the bands to the inputs of corresponding channel separators 1946-1 to 1946-10, which separate the respective bands into their constituent optical channels.

Advantageously, based on the detected signal powers and/or signal to noise ratios of the individual bands in the aggregated signal, the monitor 1926 is configured to

15 generate suitable feedback signals, e.g. on lines 1928-1 to 1928-10 or by telemetry, to corresponding variable attenuators to control the attenuation levels of the variable optical attenuators. The outputs of the respective variable optical attenuators are thereby dynamically equalized. The adverse effects of wavelength-dependent variations in the output of the amplifier and the gain-flattening filter are thereby substantially eliminated,

20 resulting in improved system performance.

Dynamic equalization using an optical performance monitor to control band attenuation level through variable optical attenuators consistent with the invention may be incorporated into a variety of optical devices in addition to multiplexers and

demultiplexers. As illustrated in FIG. 20, for example, dynamic equalization may be provided in an amplifier network element 2000 coupled to a fiber optic span between end terminals (not shown). In an amplifier configuration, the aggregated signal, e.g. λ_1 to λ_{80}, would be provided at an input to a demultiplexer or separator 2044 for separating the

5 aggregated signal into individual bands λ_1 to λ_8, λ_9 to λ_{16},...λ_{73} to λ_{80} on corresponding outputs coupled to corresponding variable optical attenuators 2012-1 to 2012-10. The outputs of the attenuators may be provided to a combiner 2014 to aggregate the bands on an output optical signal path 2050 coupled to a conventional optical amplifier 2018. The output of the amplifier may be provided to a conventional gain flattening filter 2022, and

10 a portion thereof, e.g., 1-5%, provided to performance monitor 2026 via tap 2033, for monitoring purposes and generating control signals for variable attenuators 2012-1 to 2012-10 in a manner similar to that described above with reference to Figs. 18 and 19.

The optical signal powers of the bands are substantially equalized in the manner described above with respect to the exemplary multiplexer configuration of FIG. 18. The

15 optical performance monitor 1826 at the output of the amplifier detects the output optical power of each band provides a feedback signal, e.g. on lines 2028-1 to 2028-10 or by telemetry, to each corresponding variable optical attenuator 2012-1 to 2012-10. The attenuation level of the attenuators is adjusted based on the feedback signal to achieve substantially equalized optical power in the aggregated signal on line 2050 coupled to the

20 amplifier 2018.

While the foregoing invention has been described in terms of the embodiments discussed above, numerous variations are possible. Accordingly, modifications and

changes such as those suggested above, but not limited thereto, are considered to be

within the scope of the following claims.